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Energy savings and cost–benefit analysis of using compression and absorption chillers for air conditioners in Iran

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ABSTRACT

The electricity demand in Iran has increased steadily in recent years. This is mainly due to the rapid growth in the number of high-rise air-conditioned buildings and the rapid use of electrical appliances in residential and commercial sectors. This paper investigates the annual energy required for cooling per unit area and the total energy cost per unit area for each type of air conditioning systems in different climates in Iran. The paper also investigates the effects of changing the coefficient of performance (COP) of absorption chillers on cost saving. This study found that using absorption chillers for cooling will increase the amount of energy usage per unit area; however the energy cost per unit area will decrease. In addition this research indicates that for each 0.1 increment in COP of absorption chillers, there is at least 50 USD/m^2 saved cost.

Contents

1. Introduction

Increasing population especially in urban area will increase electricity consumption in the country. The power industry in Iran, including power generation, transmission and distribution facilities, is owned, operated and administrated by the Ministry of Energy (MOE) through its executive organizations which include TAVANIR (Power Generation and Transmission Management Organization) and the regional power companies. In 2006 with over 45 GW installed nominal capacity, Iran ranked 17th in the world and 1st among the Middle East countries [1]. In 2008, electricity generation in the country reached to 214 TWh, a growth of about 5.0% in comparison to the previous year [2]. The demand for electricity has been rising steadily in recent years. Currently 33.6% of all electricity consumption is used by residential consumers [3,4]. This is mainly due to the increase in number of high-rise air-conditioned buildings and increase of using electrical appliances both in residential and commercial sectors.

Absorption cycles have been used in air-conditioning applications for over 50 years. Ammonia–water absorption equipment was found to be well suited for large capacity industrial applications that required low temperatures for process cooling. In the

Abbreviations: ADH, annual degree demand hours (h); COP, coefficient of performance (refrigeration); HD, hot and dry; HH, hot and humid; HS, hot and semi-humid; IR, inflation rate; MD, mild and dry; MH, mild and humid; PV, present value.

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Nomenclature

A	area (m^2)
C_E	electricity tariff (USD)
C_{NG}	natural gas tariff (USD)
C_t	total cost of energy for cooling per unit area (USD)
E	energy (kWh)
K	coefficient of thermal conductivity
Ra	the increase rate
R	wall resistance (m^2 °C/W)
T	temperature (°C)
U	heat transfer coefficient (W/m^2 K)
Q	heat transfer (W)
W	work transfer (W)
m	mass (kg)
x	thickness (m)
Δ	difference
$\sum$	sum

Subscripts

Av	average
E	electricity
NG	natural gas
a	ambient
i	inside
o	outside
w	wall
abs	absorption chillers
com	compression chillers

late 1950s the first working double-effect lithium bromide–water absorption chiller was built. Lithium bromide–water absorption equipment is currently used to produce chilled water for space cooling and can also be used to produce hot water for space heating and process heating. Absorption chiller is a popular alternative for conventional compression chillers when electricity is unreliable, costly, or unavailable [5].

Absorption chillers are generally classified as direct- or indirect-fired, and as single, double- or triple-effect. In direct-fired units, the heat source can be gas or some other fuel that is burned in the unit. In general, increasing the number of effects is intended to increase the COP using higher driving temperature levels [5–8]. The primary energy benefit of gas cooling systems is reduction in operating costs by avoiding peak electric demand charges and time-of-day rates. The use of gas absorption chillers eliminates the high incremental cost of electric cooling [5].

Natural gas cooling systems have greater resource efficiency than other similar electric systems. Typical electricity generation and distribution result in an approximately 65–75% loss in the initial energy resource of the fuel. In contrast, only about 5–10% of the fuel resource is lost with a gas system. Additionally, electricity costs per kW are typically three to four times more than cost per kW for natural gas, so the cost of a unit of output (refrigeration) can often be lower with an absorption unit [5]. Some of the works on thermodynamics and/or economic analyses of absorption chillers are given in Refs. [9,10].

Waste energies and renewable resources can be used to drive absorption chillers. An analysis of using solar absorption chillers for residential cooling instead of compression chillers in order to save electricity and fossil resources consequently is presented by Ref. [11]. Some of the released works on this area are given by Refs. [12–22]. Using wasted heat of gas-turbines' exhausts to drive absorption chillers by investigating the efficiency and cost saving of gas turbines while the absorption system is cooling the compressor's entrance air has been discussed by Ref. [23]. Unfortunately the COP of absorption chillers is much less than compression chillers. Some modelling investigations and augmentations of COP related to absorption chillers are widely discussed in Refs. [24–29]. Since COP individually is not a sufficient criterion to choose between absorption and compression chillers for cooling an area, therefore, HVAC engineers also are using Integrated Part Load Value (IPLV) and Applied Part Load Value (APLV). IPLV is an industry standard for calculating an annual COP based on a typical load profile and the part load characteristics of chillers. The Applied Part Load Value, APLV is calculated using the same IPLV formula, except that actual chilled and condenser water temperatures and flow rates are used. The advantage of using the APLV over the IPLV is that this rating more closely approximates actual operating conditions imposed on the chillers [5].

To compare compression and absorption chillers in economic point of view in Iran software has been developed by Ref. [30]. Cost of producing one refrigeration ton for cooling is its economic criteria. Considering geographic location and cooling load of the building, the software gets the most economic cooling system. Today, there are many types of absorption chillers in the market. They vary in size and COP as well as cost. Based on these, this paper presents the annual energy required for cooling per unit area, the total cost of energy per unit area and also the cost saving per unit area. The results lead to choosing the best type of air conditioning system in each type of climate in Iran. In addition, this paper presents the cost saving for different COPs of absorption chillers.

2. Survey data

The data used for this study are based on the outside and inside temperature, relative humidity, the electricity and natural gas prices, ADH, thermal resistance and initial cost of each type of chillers. These data were collected from Refs. [2–5]. Average monthly maximum temperature, average monthly %RH and maximum temperature in hot seasons in different type of climates in Iran are presented in Figs. 1–3 and in Tables 1 and 2. The related temperatures and annual degree demand hours are presented in Table 3. The input data used for calculation is given in Table 4.

3. Methodology

3.1. Heat transfer

The heat transfer can take place by two phenomena known as conduction and radiation. These phenomena may take place in a given system on their own, or they may occur simultaneously. As the result of conduction and/or radiation occurring into fluid media then a transport of heat may occur, called convection. Heat transfer (Q) can be expressed as [31]:

$$Q = -\frac{KA\delta T}{\delta x} \tag{1}$$

Consider a wall of thickness x (m) and an area of A (m^2). Let the outside temperature be T_o and inside temperature be T_i, as presented in Fig. 4. Temperature falls through the wall linearly, and then Eq. (1) can be written as:

$$Q = -\frac{KA(T_i - T_o)}{x} \tag{2}$$

$$Q = \frac{KA(T_o - T_i)}{x} \tag{3}$$

Let the heat transfer be per unit area, then:

$$\frac{Q}{A} = \frac{K(T_o - T_i)}{x} \tag{4}$$

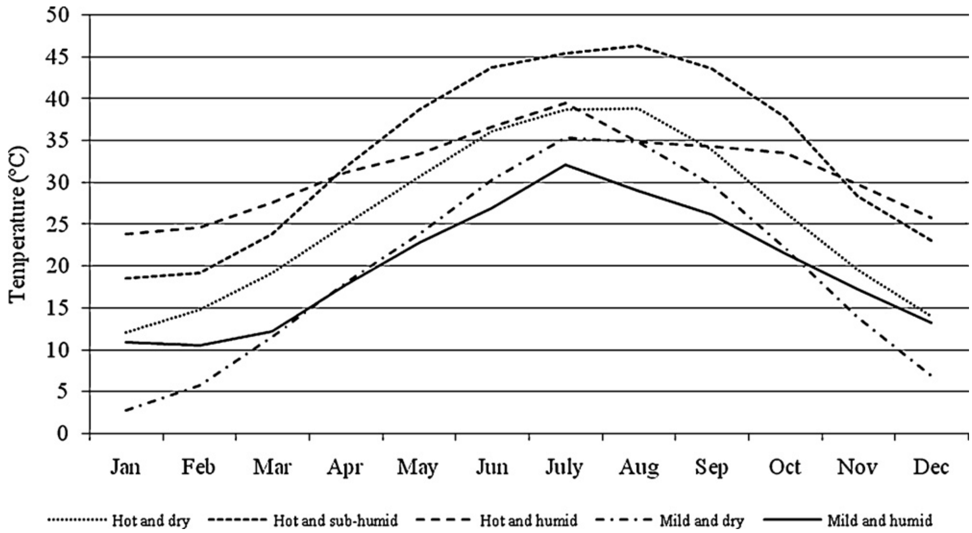

Fig. 1. Average monthly maximum temperature in each type of climate in Iran [3,4].

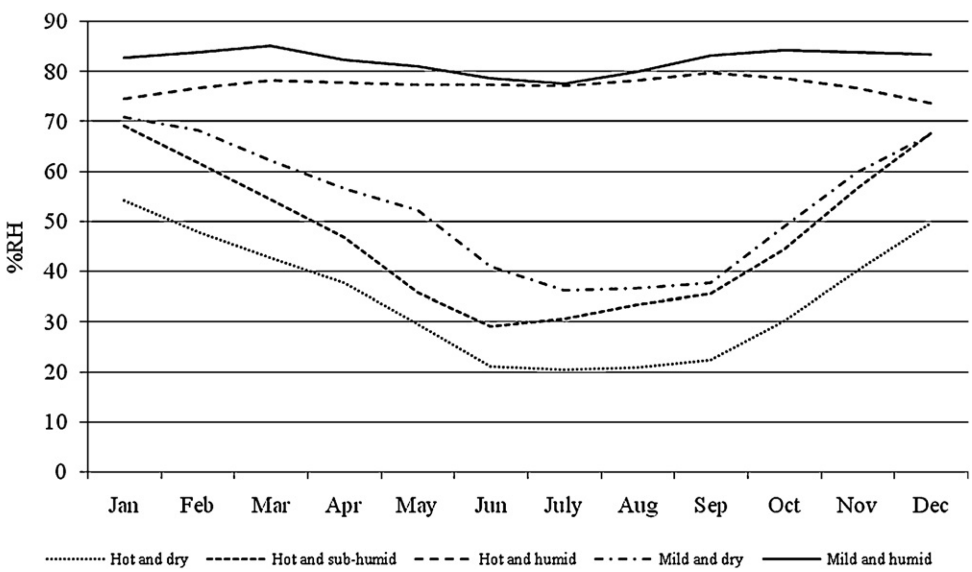

Fig. 2. Average monthly %RH in each type of climate in Iran [3,4].

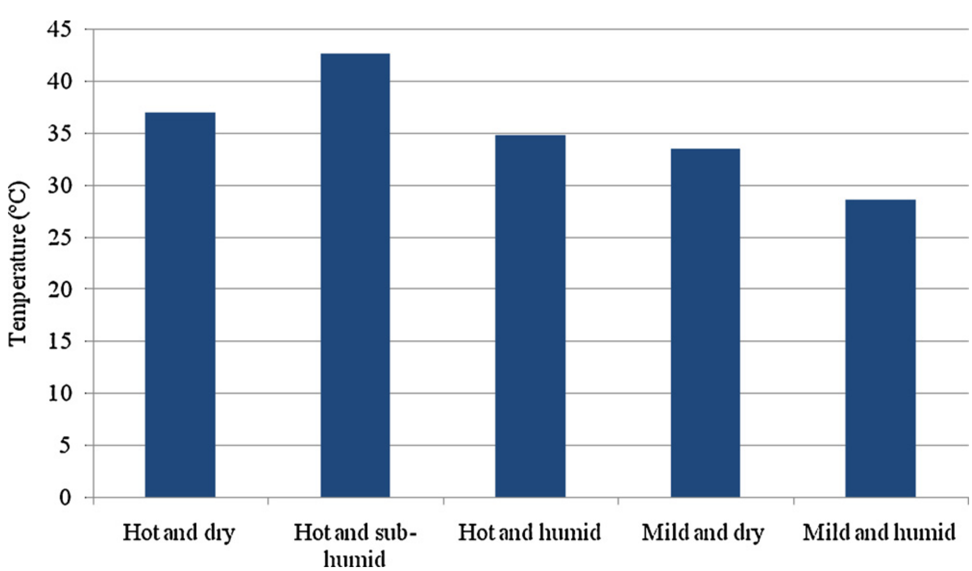

Fig. 3. Average maximum temperature in hot seasons in each type of climate in Iran [3,4].

Table 1
Regional average monthly temperatures [4].

Relative humidity monthly (%RH)					
Locality	HD	HS	HH	MD	MH
January	54.25	69.25	74.50	71.00	83.00
February	48.00	62.00	76.75	68.50	84.00
March	42.75	54.50	78.25	62.25	85.25
April	37.75	47.00	77.75	56.75	82.50
May	29.50	36.00	77.50	52.25	81.25
June	21.25	29.25	77.50	41.00	78.75
July	20.50	30.75	77.25	36.25	77.75
August	21.00	33.50	78.25	36.75	80.00
September	22.50	35.75	79.75	37.75	83.25
October	30.25	44.50	78.75	49.00	84.50
November	40.25	56.75	76.75	60.00	84.00
December	49.75	67.75	73.75	67.50	83.50
Monthly average	34.81	47.25	77.23	53.25	82.31

Table 2
Average monthly percentage relative humidity in different climates in Iran [4].

Climate	HD	HS	HH	MD	MH
Average of daily maximum temperature (°C)					
January	12.15	18.55	23.90	2.80	10.95
February	14.90	19.20	24.70	5.80	10.60
March	19.30	23.80	27.70	11.55	12.30
April	25.10	31.95	31.20	18.10	17.80
May	30.80	38.80	33.50	23.90	22.80
June	36.25	43.80	36.60	30.40	26.95
July	38.80	45.50	39.50	35.40	32.15
August	38.90	46.40	34.90	34.85	29.10
September	34.00	43.65	34.40	29.80	26.20
October	26.55	37.90	33.55	22.15	21.60
November	19.70	28.40	29.85	13.90	17.30
December	14.05	23.05	25.80	6.95	13.30
Monthly average	25.87	33.42	31.30	19.63	20.09
Average of daily minimum temperature (°C)					
January	−2.10	6.90	13.75	−7.90	2.85
February	0.45	8.50	15.15	−5.35	3.05
March	5.10	12.30	18.30	−0.65	5.45
April	10.10	17.30	21.70	4.20	9.65
May	14.65	22.55	25.10	7.90	14.40
June	19.00	25.65	28.00	11.65	18.30
July	20.70	27.55	29.25	15.95	20.65
August	18.15	26.65	28.65	15.25	20.60
September	13.65	22.90	26.65	10.10	18.15
October	8.05	18.15	23.20	5.55	13.65
November	2.30	12.85	18.65	0.85	8.90
December	−1.25	8.20	15.10	−3.70	4.85
Monthly average	9.07	17.46	21.96	4.49	11.71

In a composite wall, Q passes through each layer of the wall. Hence, Q can be written as:

$$Q = \frac{A(T_o - T_i)}{\sum(x/K)} \tag{5}$$

where x is the thickness of each layer of the wall, and K the respective coefficient of thermal conductivity. Eq. (5) per unit area then becomes:

$$\frac{Q}{A} = \frac{T_o - T_i}{\sum(x/K)} \tag{6}$$

From the second law of thermodynamics, it is known that there must be a temperature difference between the surface and the surroundings or ambient to be heat transfer. The heat transfer will include conduction, radiation and convection. Although particular wavelengths of radiation are absorbed by opaque surfaces, heat transfer by radiation requires a transparent medium. Radiations striking a building wall are not significant as only a fraction of this is absorbed and are accountable for the overall heat transfer. Hence, radiation is not taken into consideration while calculating the heat transfer through the building walls.

Table 3
Related temperatures and annual degree demand hours [4].

Description	Unit	HD	HS	HH	MD	MH
Design temperature, outside air T_o	°C	41.0	47.0	43.5	37.0	35.0
Design temperature, inside air T_i	°C	24.0	26.6	26.5	24.0	24.0
Average outside temperature	°C	36.7	42.7	38.4	33.5	31.2
Annual degree demand hours, ADH	h	945.0	2160.0	3360.0	360.0	720.0

Table 4
Input data [3–5].

Description	Unit	Values
Life cycle period, N	years	15
Resistance of the wall, R_w	m^2 °C/W	0.30
Electricity tariff, C_E	USD/kWh	0.02
Natural gas tariff, C_{NG}	USD/m^3	0.07
Initial cost of absorption chillers, $I.C._{abs}$	USD/m^2	30.00
Initial cost of compression chillers, $I.C._{com}$	USD/m^2	13.75
The increasing of electricity tariff per year, Ra_E	%	7
The increasing of natural gas tariff per year, Ra_{NG}	%	1
Natural gas calorific value	MJ/m^3	40
Inflation rate, IR	%	10
COP of absorption chillers		0.9
COP of compression chillers		2.9

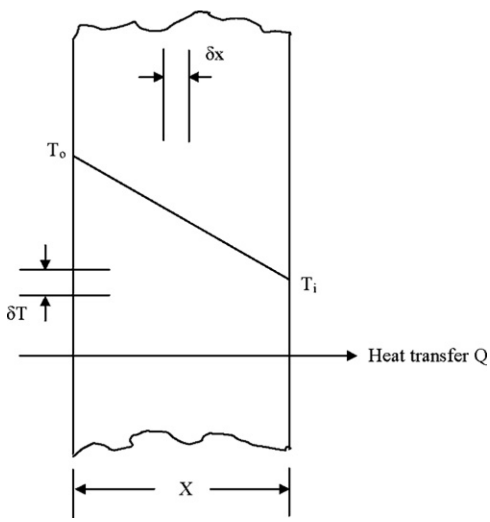

Fig. 4. Heat transfer through a wall.

The heat flow from the ambient air to the wall surface thus becomes [31]:

$$Q = h(T_a - T_w) \tag{7}$$

Q passes through each layer of the wall, the solution at the surface becomes:

$$Q = UA(T_o - T_w) \tag{8}$$

This per unit area becomes:

$$\frac{Q}{A} = U\Delta T \tag{9}$$

where U, the heat transfer coefficient is:

$$U = \frac{1}{1/h_o + x_1/K_1 + x_2/K_2 + \cdots + x_n/K_n + 1/h_i} \tag{10}$$

where, h_o and h_i are the convection heat transfer coefficients for outside and inside surfaces, K_1, K_2, etc. are thermal conductivity of wall layers, and x_1, x_2, etc. are their thicknesses. The denominator of Eq. (9) is named R_w and expressed in Eq. (11):

$$R_w = \frac{1}{h_o} + \frac{x_1}{K_1} + \frac{x_2}{K_2} + \cdots + \frac{x_n}{K_n} + \frac{1}{h_i} \tag{11}$$

Hence, the heat transfer coefficient of the wall can be expressed as:

$$U = \frac{1}{R_w} \tag{12}$$

The annual energy required for cooling (E) can be expressed as a function of annual degree demand hours (ADH; given in hours) of the air conditioner and the heat transfer (Q), that can be concluded by the following equation:

$$E = \frac{\text{ADH} \times Q}{\text{COP}} \tag{13}$$

COP is the coefficient of performance for air conditioner. And ADH is calculated using operating hours of air conditioners and the temperature ratio, $(T_{o,Av} - T_i)/(T_o - T_i)$ where $T_{o,Av}$, T_o and T_i indicate annual average outside temperature, temperature of outside air and temperature of inside air, respectively [32,33]. Therefore, annual energy required for cooling per unit area can be expressed as:

$$\frac{E}{A} = \frac{\text{ADH} \times \Delta T}{R_w \times \text{COP}} \tag{14}$$

3.2. The annual cost of energy per unit area

The annual energy per unit area required for cooling can be calculated for both absorption and compression chillers. Electricity and natural gas tariffs are used to calculate the total cost of energy for cooling per unit area (C_t). Hence, the total cost of energy per unit area for compression chillers (C_t) can be calculated as follows [32–37]:

$$C_t = \frac{E}{A} \times C_E \tag{15}$$

where C_E is the electricity tariff, and by combining Eqs. (13) and (14) gives:

$$C_t = \frac{\text{ADH} \times \Delta T \times C_E}{R_w \times \text{COP}} \tag{16}$$

On the other hand, for absorption chillers, CNG is used to calculate the total cost of energy per unit area. Firstly, the natural gas tariff unit is converted from (USD/m^3) to (USD/kWh) by using natural gas calorific value, then this converted natural gas tariff is used to calculate the total cost of energy per unit area. Hence, the total cost of energy per unit area for absorption chillers (C_t) can be calculated as follows [32–38]:

$$C_t = \frac{E}{A} \times C_{NG} \tag{17}$$

where C_{NG} is the natural gas tariff, and by combining Eqs. (14) and (17) gives:

$$C_t = \frac{\text{ADH} \times \Delta T \times C_{NG}}{R_w \times \text{COP}} \tag{18}$$

3.3. The cost saving per unit area

In order to calculate the cost savings over the life cycle period (N) years for each climate, it is important to find out the present value (PV) of each type of air conditioning systems [37]. Present value for compression chillers can be expressed in relation with the total energy cost per unit area (C_t), the increase rate of electricity tariff (Ra_E), life cycle period (N) and the inflation rate (IR):

$$\text{PV}_{com} = (\text{I.C.})_{com} + \sum_{n=1}^{N} C_t(1 + Ra_E)^{n-1}(1 + IR_E)^{-n} \tag{19}$$

Present value for absorption chillers can be expressed in relation with the total cost energy per unit area (C_t), the increase rate of natural gas tariff (Ra_{NG}), life cycle period (N) and the inflation rate (IR):

$$\text{PV}_{abs} = (\text{I.C.})_{abs} + \sum_{n=1}^{N} C_t(1 + Ra_{NG})^{n-1}(1 + IR_{NG})^{-n} \tag{20}$$

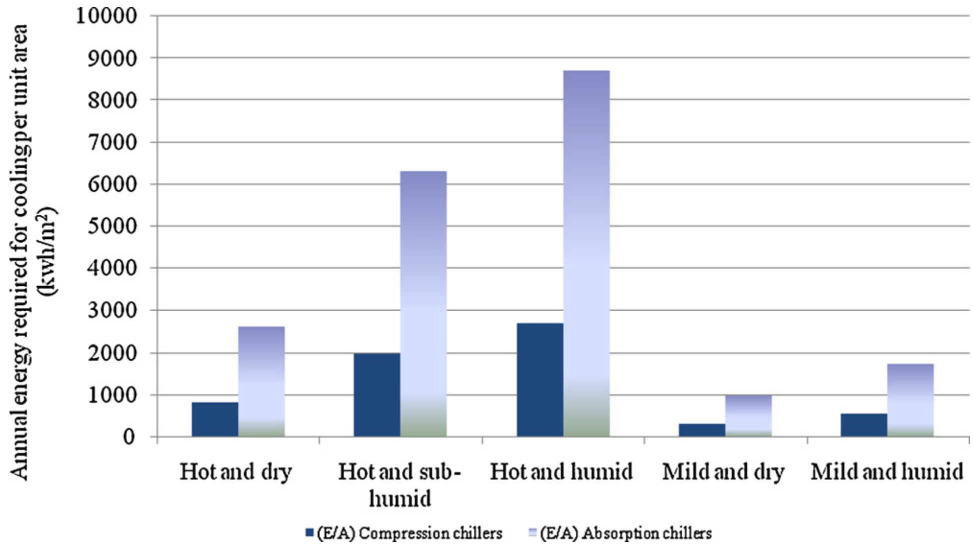

Fig. 5. Annual energy required for cooling per unit area in both air conditioning systems.

In Eqs. (18) and (19) the term $C_t(1+Ra_{NG})^{n-1}$ shows the total energy cost per unit area in each year (S).

Present value for each type of air conditioning systems is calculated by using these two formulas and the difference between these two is the cost saving per unit area in each climate:

$$\Delta PV = \left| PV_{com} - PV_{abs} \right| \tag{21}$$

4. Results and discussion

Based on temperature and humidity, Iran has been categorized into five different climates [4]. In regards to maximum dry bulb temperature in summer, different areas are divided into two parts, hot and mild:

- Hot areas, the dry bulb temperature is higher than 40 °C (105 °F).
- Mild areas, the dry bulb temperature is lower than 40 °C (105 °F).

Another factor that affects this category is the humidity. Three different groups of humidity are defined, humid, semi-humid and dry.

- Dry areas where wet bulb temperature is lower than 23 °C (73 °F).
- Semi-humid areas where wet bulb temperature is between 23 °C and 28 °C (73 and 85 °F).
- Humid areas where wet bulb temperature is higher than 28 °C (85 °F).

Based on the above criteria, the general classification is defined as follows; hot and dry, hot and semi-humid, hot and humid, mild and dry and finally mild and humid. Tables 1 and 2 show regional average monthly temperature and average of monthly percentage relative humidity in different climates, respectively.

Fig. 5 illustrates the annual energy required for cooling per unit area for absorption chillers and compression chillers in all types of climates in Iran. The calculated results show that the annual energy required for cooling per unit area for absorption chillers is more than the compression chillers in all climates. Due to the high annual degree demand hours, ADH, and also low coefficient of performance, COP, of absorption chillers in hot climates, the difference between annual energy required for cooling per unit area for compression and absorption chillers is more sensible.

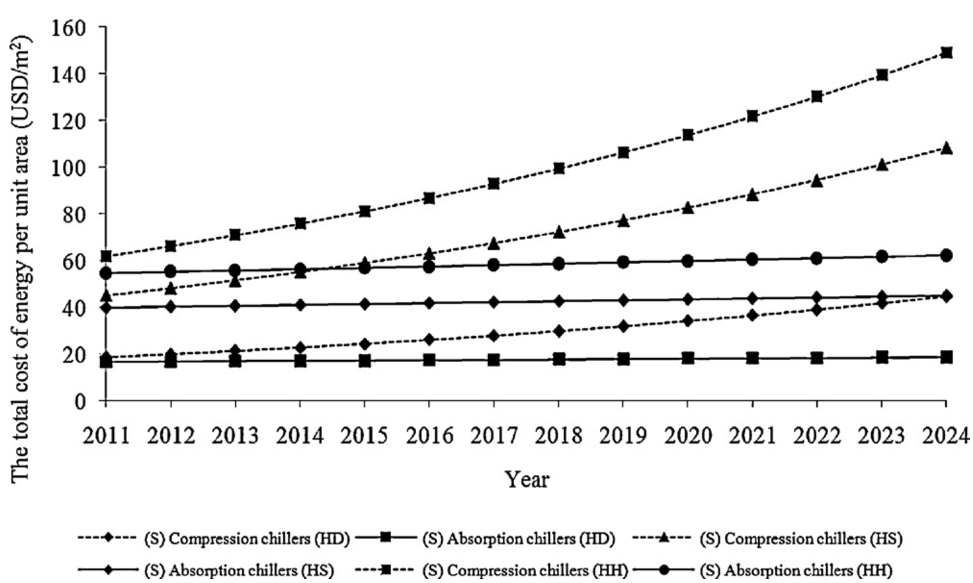

Fig. 6. The total cost of energy per unit area in all hot climates for both air conditioning systems.

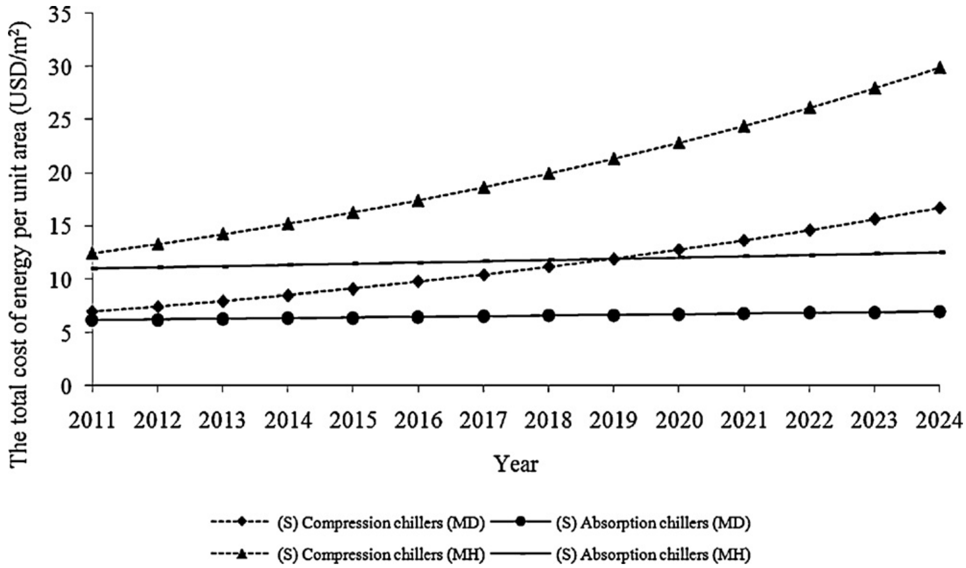

Fig. 7. The total cost of energy per unit area in all mild climates for both air conditioning systems.

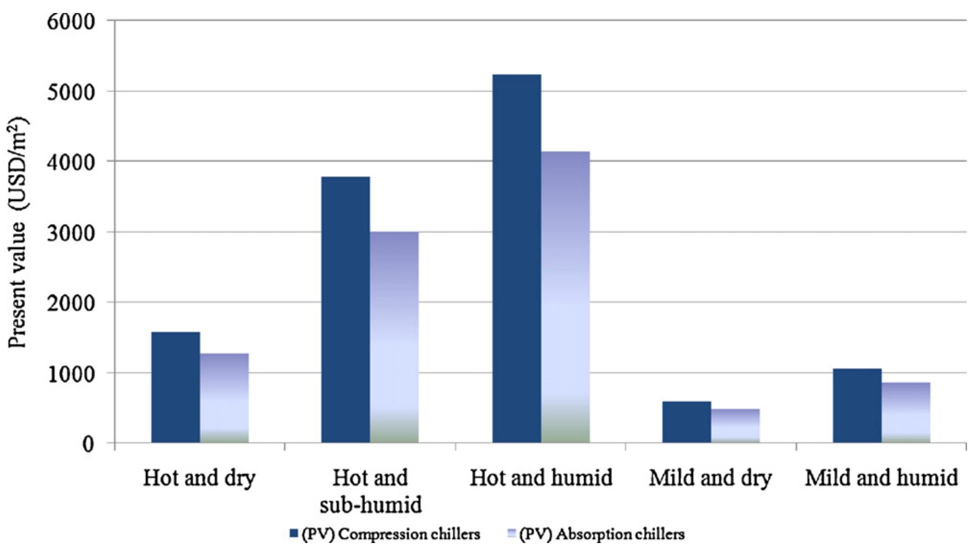

Fig. 8. Present value in each type of climate for both air conditioning systems in Iran.

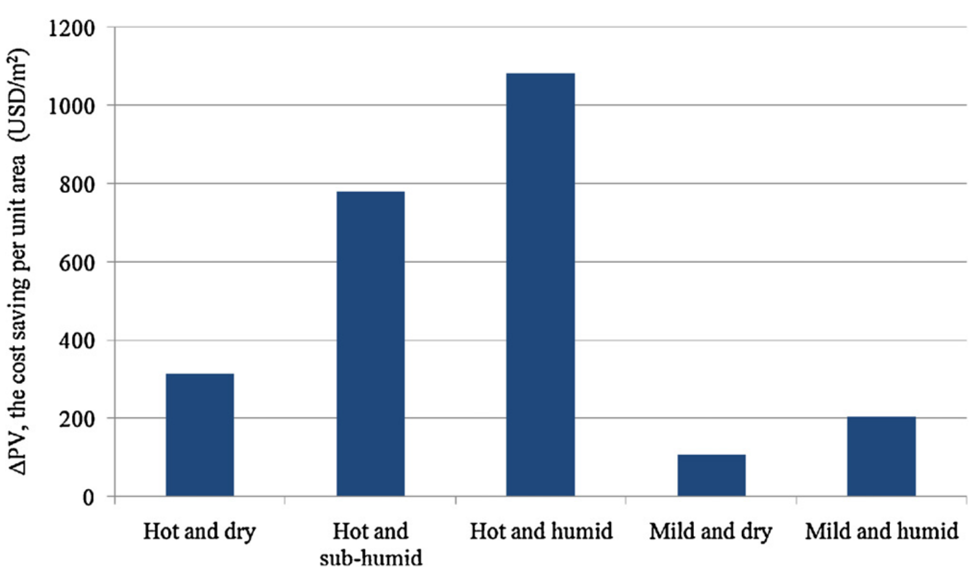

Fig. 9. The cost saving per unit area in each type of climate.

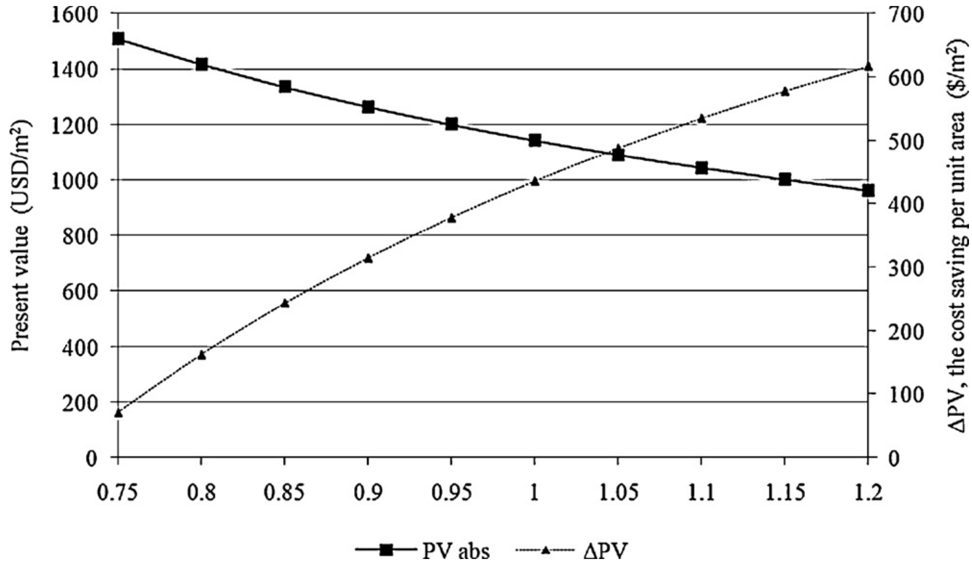

Fig. 10. Present value and the cost saving per unit area in hot and dry climate for different COPs in absorption chillers.

Iran has the second largest reserves of natural gas in the world after Russia; this makes the price of natural gas in Iran much lower than electricity. Figs. 6 and 7 show the total energy cost per unit area (S) for both absorption and compression chillers in all climates for 15 years. These estimations show the total energy cost per unit area in all climates is higher for compression chillers. Moreover, the difference between the amount of S in absorption and compression system is rising by the years.

While the energy cost per unit area (S) of absorption chillers is roughly a constant number along these 15 years, a steady upward trend of S for compression chillers can be observed. In addition, the highest difference between energy cost per unit area of absorption and compression cooling systems has been occurred in hot and humid climate. In mild provinces, the rate of S for humid areas is more than dry areas. However, the annual energy required for cooling per unit area in absorption chillers is more (Fig. 5) but due to the price of natural gas and electricity in Iran, the total cost of energy per unit area for compression chillers is more than absorption chillers.

Fig. 8 shows the present value in each type of climate for both air-conditioning systems in 14 years life cycle period. Although the initial cost of absorption chillers with the same refrigeration ton is more than compression chillers in all climates, but since the price of natural gas is lower than electricity and also the increase rate of this price is lower, absorption chillers gained a smaller present value. It is shown that among absorptions and compressions air-conditioning systems, the most economic types are absorption chillers in all types of climates. This result reached at by considering initial cost, annual energy requirement for cooling per unit area, the electricity and natural gas tariffs, the increasing rate of electricity and natural gas tariffs and a fixed COP for any type of chillers.

The present value in each type of climate for both absorption and compression systems has been presented in Fig. 9. The cost–benefit analysis per unit area has been presented in Fig. 9 for 14 years. The calculated results in Figs. 5–9 are for absorption chillers with COP equal to 0.9 and compression chillers with COP of 2.9. The highest present values are gained for hot climates because of higher ADH and higher difference between inside and outside design temperatures in these climates. It bears mentioning, that the highest cost saving is for hot and humid climates.

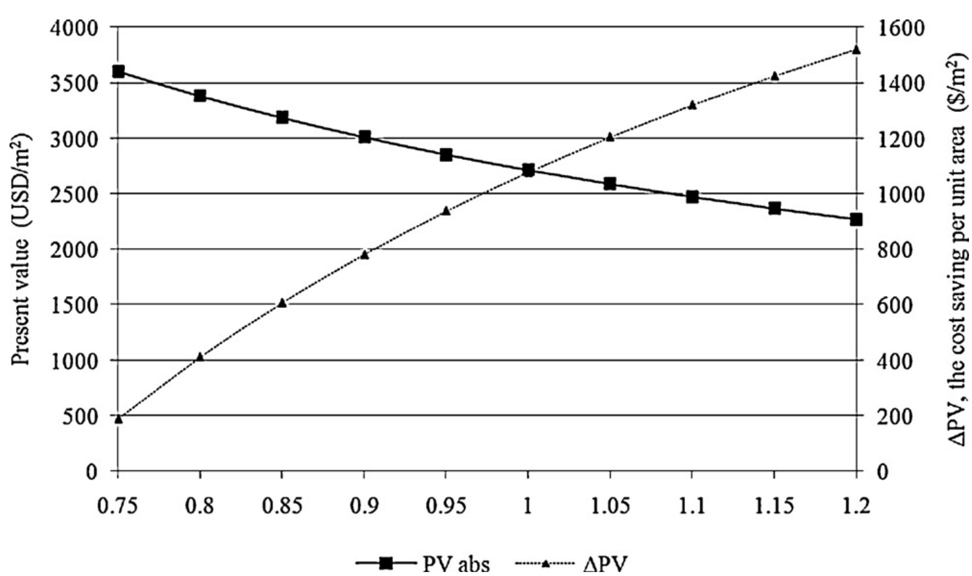

Fig. 11. Present value and the cost saving per unit area in hot and sub-humid climate for different COPs in absorption chillers.

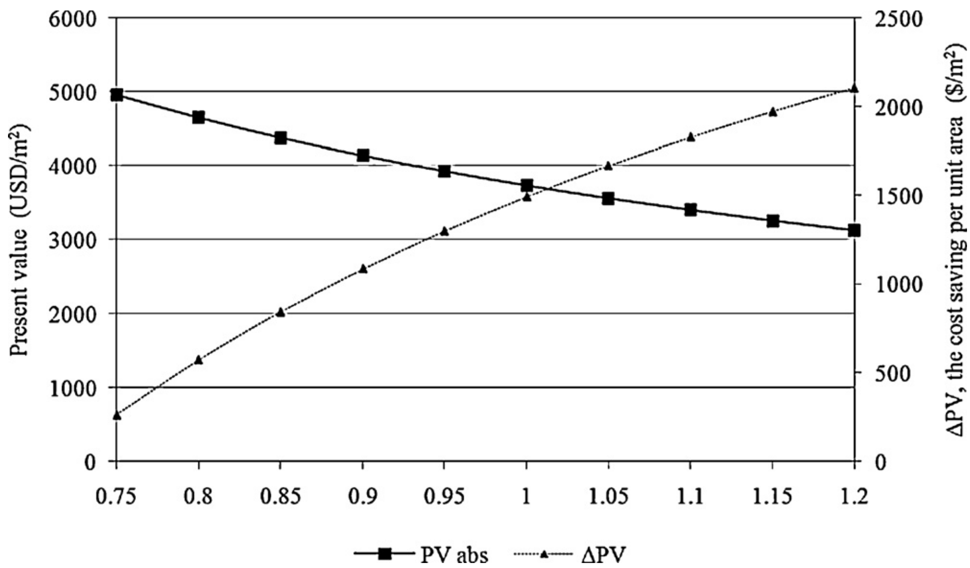

Fig. 12. Present value and the cost saving per unit area in hot and humid climate for different COPs in absorption chillers.

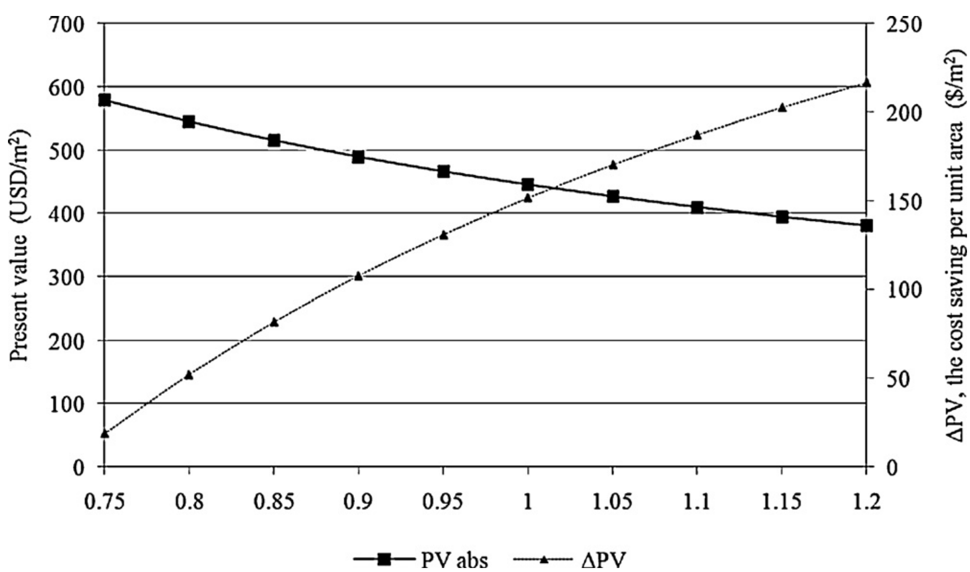

Fig. 13. Present value and the cost saving per unit area in mild and dry climate for different COPs in absorption chillers.

Table 5
Different prices assumed for absorption chillers.

COP	0.75	0.8	0.85	0.9	0.95	1	1.05	1.1	1.15	1.2
Price (USD/m^2)	26	27	28	29	30	31	32	33	34	35

Present value and cost saving per unit area in all climates for different COPs of absorption chillers are shown in Figs. 10–14. Table 5 illustrates the different prices assumed for absorption chillers, also as mentioned before for compression chillers COP has been assumed equal to 2.9. Figs. 10–14 show that while present value of absorptions decrease linearly with raising the amount of COP, the cost saving per unit area is increasing.

The present value of compression chillers has been illustrated in Table 6. The present value of absorption chillers in all types of climates is less than this value for compression chillers. The highest cost saving per unit area can be seen in hot and humid climate for COP of 1.2. This is due to high annual degree demand hours and high temperature difference between indoor and outdoor.

Table 6
The present value of compression chillers.

Climate	HD	HS	HH	MD	MH
P.V. (USD/m^2)	1577.6	3789.8	5224	596.5	1057

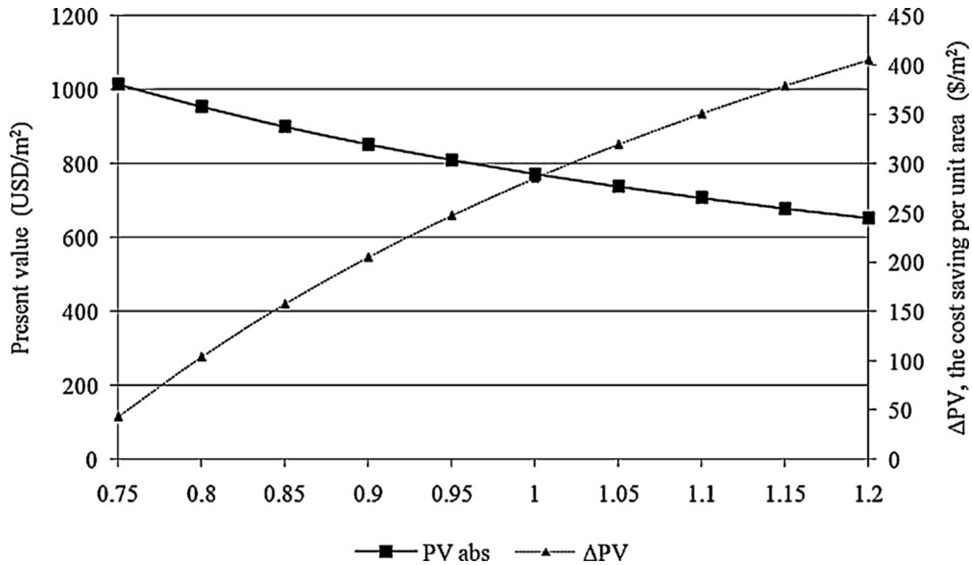

Fig. 14. Present value and the cost saving per unit area in mild and humid climate for different COPs in absorption chillers.

5. Conclusions

This paper analysed the annual energy demand per unit area and the total energy cost per unit area in different type of climates for both absorption and compression chillers in Iran. The cost of energy per unit area was calculated using annual energy demand for cooling per unit area, electricity and natural gas tariffs.

The total saved cost was calculated considering life cycle analysis. The paper indicated that although the annual energy required for cooling per unit area for absorption chillers is more than compression chillers, but since the cost of each unit of natural gas is lower than electricity, the total energy cost per unit area of absorption chillers for all climates is much less than compression chillers.

For each 0.1 increment in COP of absorption systems from 0.75 to 1.2 there is at least 50 USD/m^2 saved cost for cooling; this amount is around 500 USD/m^2 for hot and humid provinces. Moreover, a vast area of Iran has a hot and humid climate, therefore being a big economic motivation to use an absorption system. Hence, this study can serve as a good guide for the governments in the region with similar conditions to encourage companies and individuals to produce and use absorption chillers.

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